High Frequency Acoustic Reflection and Transmission in Ocean Sediments

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Award Number: N00014-09-1-0404
N00014-03-1-0242
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LONG-TERM GOALS

Development of a physical model of high-frequency acoustic interaction with the ocean floor, including penetration through and reflection from smooth and rough water/sediment interfaces, scattering from the interface roughness and volume heterogeneities and propagation within the sediment. The model will aid in the detection and classification of buried mines and improve SONAR performance in shallow water.

OBJECTIVES

1) A comparative study of acoustic sediment interaction models including visco-elastic, Biot, BICSQS, and grain shearing and scattering models including perturbation theory, small slope approximation and finite element models through careful comparison with experimental measurements of the bistatic return, for the purpose of defining the best physical model of high-frequency acoustic interaction with the ocean floor.

2) An inversion methodology that can provide input parameters for the resulting physical model from reflection coefficient measurements.

3) New finite element modeling capability for acoustic sediment interactions.

APPROACH

Our approach to this problem has three distinct areas of concentration: 1) On going analysis of experimental reflection coefficient data, 2) Development of a finite element model of scattering from rough interfaces as an aid in understanding difficult physical phenomena that are beyond the capabilities of existing models, and 3) Improving the methodology for the inversion of reflection coefficient data to overcome the effects of propagation and scattering.

WORK COMPLETED

The main achievements of 2009 include:

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2009**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2009 to 00-00-2009**

4. TITLE AND SUBTITLE **High Frequency Acoustic Reflection And Transmission In Ocean Sediments**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The University of Texas at Austin,Applied Research Laboratories,Austin,TX,78713**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

1) Development of a comprehensive rough bottom scattering model to include scattering via the Kirchhoff approximation that accounts for spherical wave effects and poro-elastic effects. This model is then applied to the analysis of data from the EVA sea test conducted in October 2006 off the coast of Isola d'Elba.

2) Development and validation of a Finite Element Model for rough interface scattering and its application to shallow water propagation and reverberation modeling.

3) Preliminary three-dimensional finite element rough bottom scattering model.

Comprehensive Scattering Model.

There are three factors that can significantly effect reflection coefficient measurements, the underlying sediment model, spherical wave effects and interface scattering. All of these factors must be considered in order to produce a comprehensive scattering model for the water sediment interface. The underlying sediment models can be complex and include poro-elastic effects. Previously, these were incorporated into spherical wave or scattering models via an effective density and frequency dependent sound speed (Williams, 2001.) These effects are now directly incorporated into a plane wave decomposition model for spherical waves. (Camin, 2005.) The results from these models are used with the Kirchhoff approximation to compute the scattered field through a surface integral. Using a measured roughness spectrum, statistics of the scattered field are computed through numerous realizations. The effect of each of these effects can be significant. In Figure 1 is shown each of the factors and its effect on the modeled value of the reflection coefficient as a function of angle at a frequency of 10 kHz. The model parameters are based on the Experimental Validation of Acoustic modeling techniques (EVA) sea test conducted off the coast of Isola d'Elba in 2006.

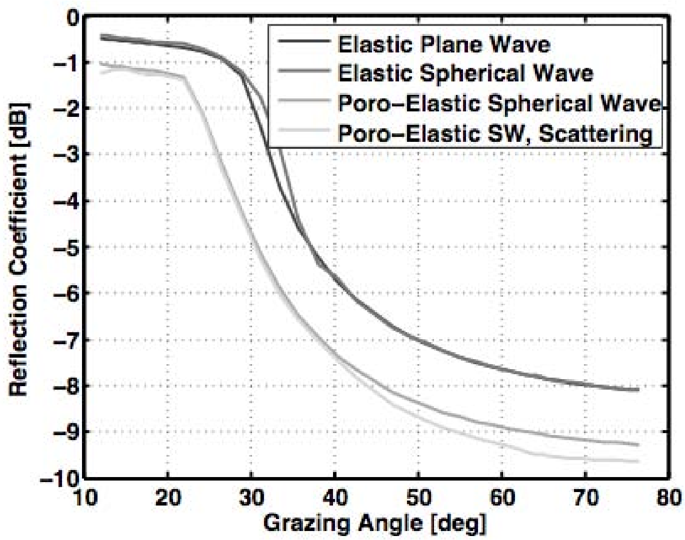

Figure 1: Factors influencing reflection coefficient measurements. Shown is an elastic plane wave model compared with an elastic model including spherical wave effects, a poro-elastic model, and a model including spherical wave effects, poro-elastic effects and scattering. All models are computed at 10 kHz.

[The results from four models of reflection at 10 kHz are shown. The plane wave elastic model has the highest reflection coefficient prediction. Adding spherical waves decreases the values slightly near the critical angle. The poro-elastic model is 1-2 dB lower across the curve. Adding scattering effects decreases the values an addition 0.5 dB near normal incidence.]

Application of FEM Scattering to Propagation Modeling

The finite element model developed for scattering has been applied to propagation. Specifically, the transmission loss for a shallow waveguide with rough interfaces and range dependent sound speed profiles has been computed. Two domains, shown in Figure 2, were considered both based on analysis of sea test data. The first domain includes two layers with flat interfaces in 100 m deep waveguide. The second domain includes a range dependent sound speed profile as well as rough interfaces on both interfaces. The water/sediment interface is based on a power law roughness derived from typical parameters. The sediment/sediment interface is periodic.

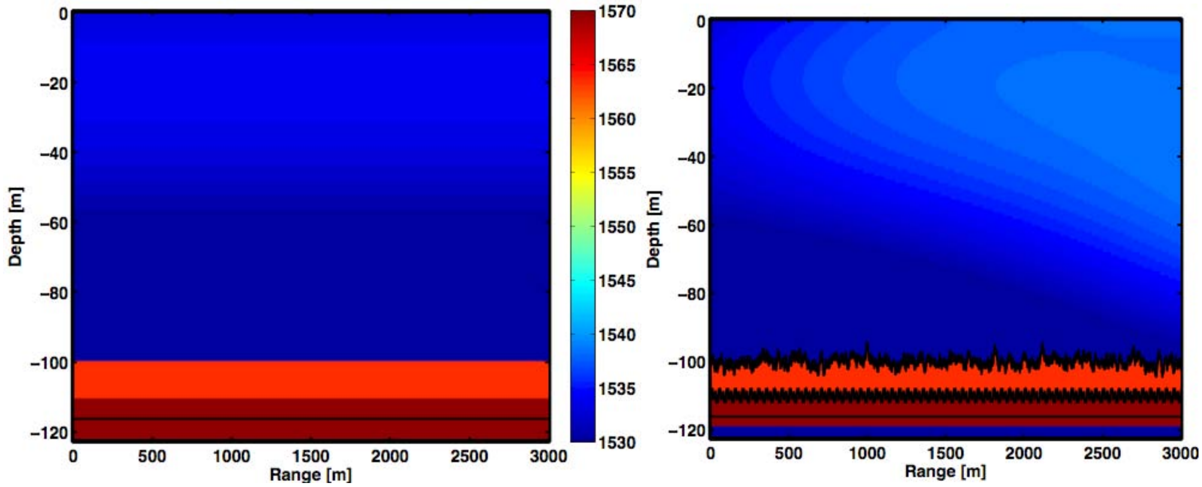

Figure 2: Two finite element domains for a shallow water waveguide. In the first domain (left), the geo-acoustic properties are range independent. In the second domain (right), the geoacoustic properties vary with range and a rough interface is included at the water/sediment interface and between the layers.

[Two wave guides are shown, both with water depths of 100 m and a 10 m sediment layer over a faster sub-bottom. The left waveguide is range independent although there is a depth dependent sound speed in the water column. The right waveguide has range dependent sound speed profile as well as rough interfaces for the two layers.]

Three-dimensional Scattering Model

In order to quantify the effects of three dimensional scattering, the scattering of a spherical incident wave by a rough, pressure release surface was modeled using the commercially available finite element (FE) code COMSOL. A measured seafloor roughness spectrum was used to generate random realizations of a rough surface. The FE code calculates the scattered pressure on the surface and the Helmholtz-Kirchhoff integral is applied to compute the pressure at an arbitrary point away from the surface. Use of the Helmholtz-Kirchhoff integral permits both the source and receiver to be located outside of the FE domain, greatly reducing the domain size. An example of a rough surface realization is shown below in Figure 3 (a), and an example of its embedding in the finite element model is shown in Figure 3(b).

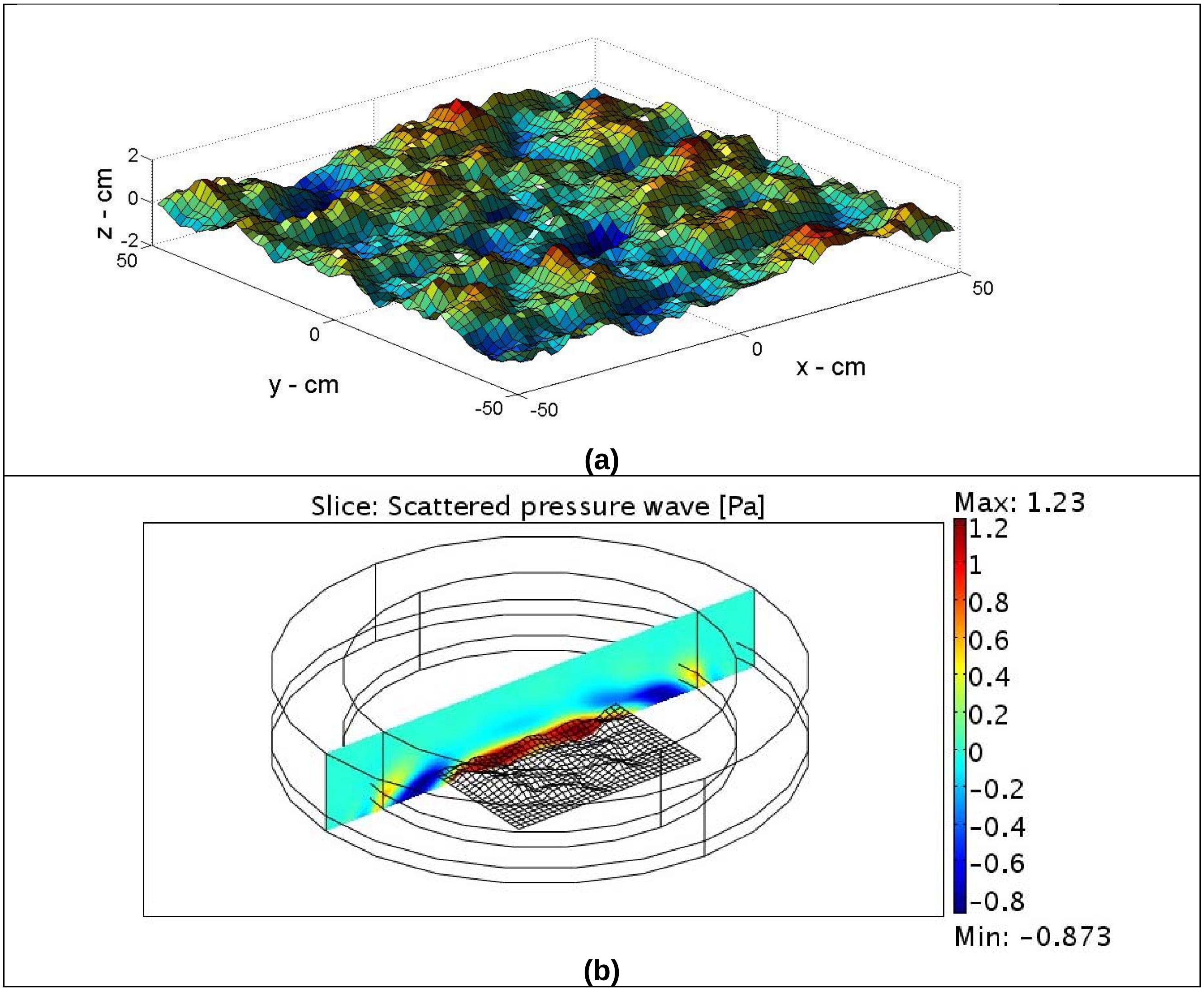

Figure 3: (a) An example of a rough surface generated from measured data (b) An example solution from the finite element (FE) code, where the pressure is computed within the FE domain. The Helmholtz-Kirchhoff integral is then used to calculate the pressure at receiver points outside of the FE domain.

[In figure (a), a 50 cm by 50 cm section of the rough interface is shown. The RMS height is less than 1 cm. In figure (b), the pressure above the surface is shown in arbitrary units. The pressure is highest in the center. Minimums exist on the edges.]

RESULTS

Comprehensive Scattering Model.

The experimental data from the EVA experiment were compared with the new comprehensive scattering model and results for the magnitude of the reflection coefficient are shown in Figure 4. In the right figure is shown the data at 20 kHz compared to three models, the flat interface model using plane wave decomposition and poro-elastic effects, a model that also includes scattering effects based on a Kirchhoff model with Gaussian distributed roughness and a model which includes all effects with a interface roughness based on measured roughness statistics. Included are reflection coefficients computed from the peak of the reflected signal, peak values, and from the integral of the received intensity, energy values. It is shown that the energy values are less influenced by scattering and approach the reflection coefficient of the flat interface model. The peak values are heavily influenced by scattering and are only modeled well by a scattering model based on the measured roughness. The models also account for the highly frequency dependent nature of the peak values as shown in the left figure.

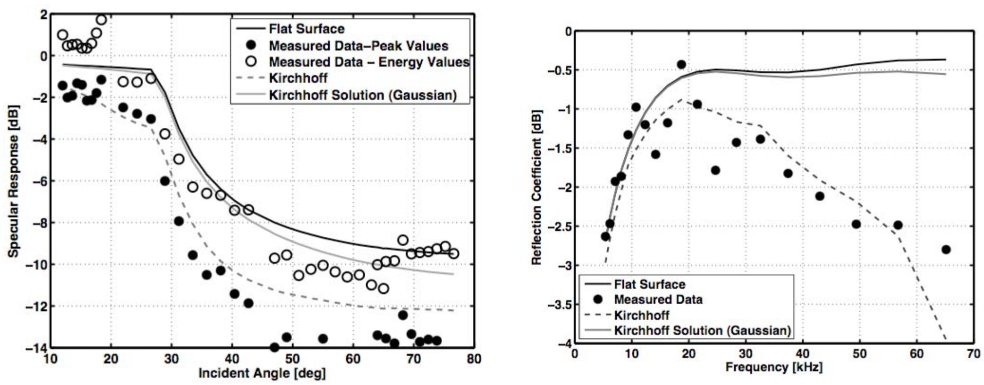

Figure 4: The measured reflection coefficient compared to the comprehensive scattering model. The left figure shows the reflection coefficient magnitude at 20 kHz compared to the flat surface model, Kirchhoff model based on a Gaussian roughness and the Kirchhoff model based on the measured spectrum. The right figure shows the data at 20 degrees grazing compared to the same models. The left figure includes reflection coefficients computed from energy and peak values. The right figure only has the reflection coefficient from peak values.

[Shown on the left are the data compared with the models as a function of angle. The peak values agree well with the flat surface except at very shallow angles and between 45 and 60 degrees. The energy values are consistently below the Kirchhoff scattering solution using the experimentally measured power spectrum for grazing angles larger than critical. The right figure shows that the peak values agree with the general trend of the Kirchhoff scattering solution using the measured power spectrum.]

Application of FEM Scattering Model to Propagation

The transmission loss was calculated using finite elements on a two-dimensional domain for the waveguides shown in Figure 2. These values are compared in Figure 5. The range dependent model has much greater loss, more than 10 dB at a range of 6 km. This is most likely due to scattering into the sediment from the rough interface.

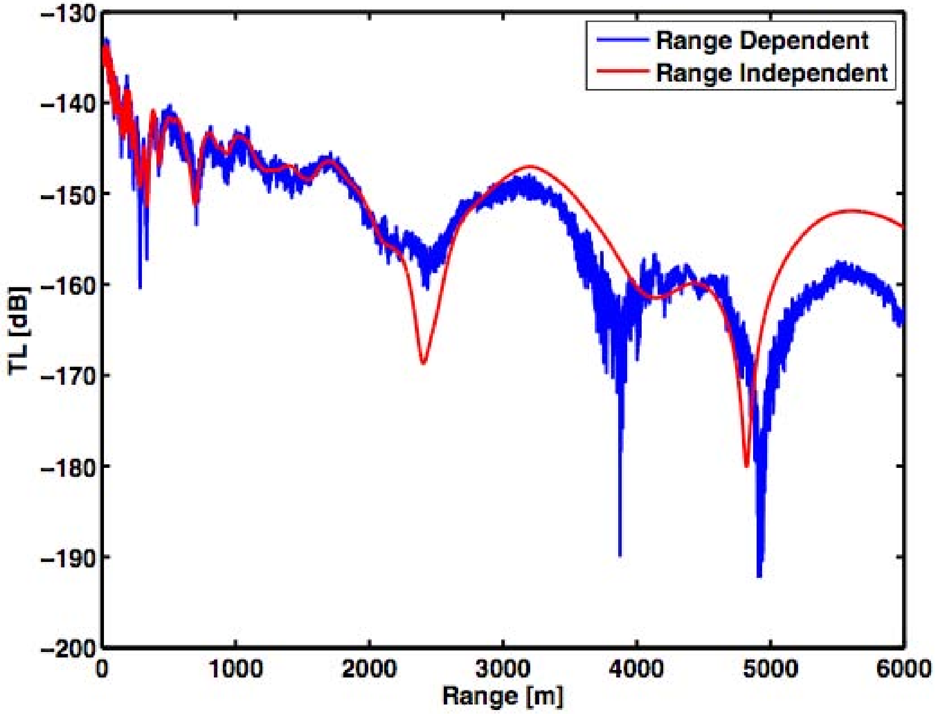

Figure 5: Transmission loss as a function of range for the range-dependent and range-independent waveguides. Including range dependence leads to losses in the waveguide.

[Shown is the comparison of the transmission loss for the range independent and range dependent waveguides. The range dependent waveguide deviates from range independent waveguide starting at 2 km. At 6 km, the solutions are separated by approximately 10 dB.]

Three-dimensional Scattering Model

The FE model was compared with the Kirchhoff Approximation (KA) in three dimensions and an exact solution to the three dimensional integral equation for the case of a spherical wave incident on a pressure release surface. Preliminary results show the average error in the scattered pressure field between the FE, KA, and integral equation model to be less than 1 dB. The effect of discretization density, surface scattering area, incident angle, and the surface RMS roughness on the validity of the various models is currently under investigation. As an example, shown below is a slice of the scattered pressure field as computed by the FE (Figure 6(a)) and KA (Figure 6(b)) codes.

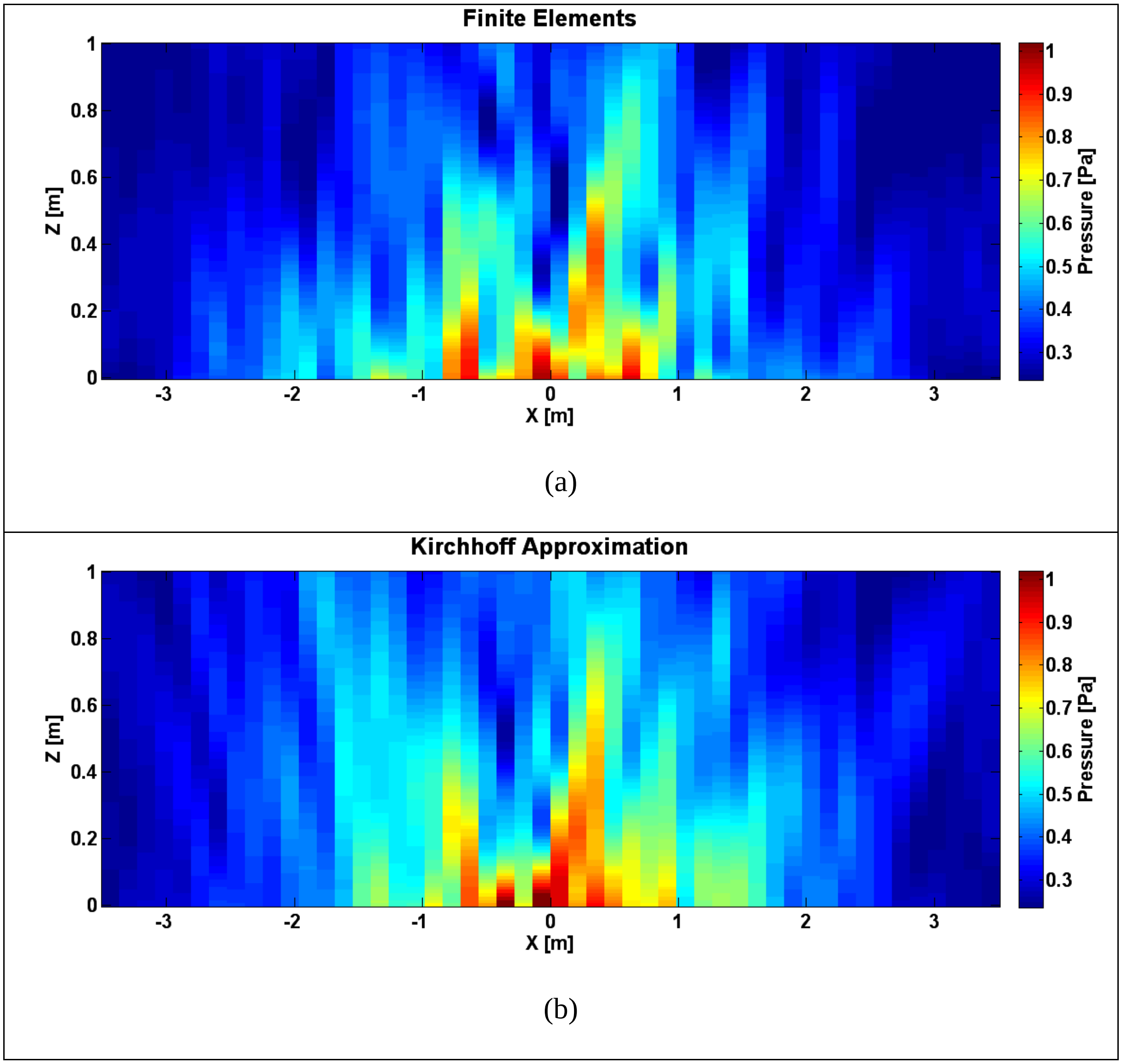

Figure 4: A comparison of the scattered pressure field from (a) Finite Element Method and (b) Kirchhoff Approximation.

[Shown is a comparison of the pressure field from the finite element method and Kirchhoff approximation. The pressure is concentrated in the center, but there is significant pressure to at least 1 m from the surface. The fields agree qualitatively.]

IMPACT/APPLICATIONS

All of the current standard acoustic propagation and scattering models that have been accepted and certified by the Navy's Ocean Acoustic Mathematical Library (OAML) approximate the ocean sediment as a visco-elastic medium with a flat interface. This study has identified the effects of a rough interface which predicts significant difference in the mean values of reflection loss at sub-critical angles at higher frequencies. This has impact in long-range propagation models for ASW applications, particularly in littoral environments where the propagation loss is largely controlled by bottom reflection loss.

RELATED PROJECTS

This project is closely related to other projects under the ONR "High Frequency Sediment Acoustics" thrust since the environmental inputs required for analysis are dependent on other projects within the thrust. We collaborated with the NATO Undersea Research Center both to perform the EVA sea test and for information sharing on FEM methods. The finite element scattering method is also being applied to low frequency littoral propagation modeling through an internal ARL research initiative.

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